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Taguchi-Based GRA for Parametric Optimization in Turning of AISI L6 Tool Steel Under Cryogenic Cooling

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Abstract. Cutting fluids have frequent use in industrial sector to improve the machinability. Due to the negative impact on our ecology, recent focus has shifted to explore some environment-friendly cooling techniques such as cryogenic cooling. Cryogenic cooling involving liquid nitrogen is one of the alternative techniques which improves the efficiency of the machining process and is environmentally friendly as well. In current work, cutting parameters in turning such as cutting speed and feed rate were optimized under cryogenic cooling for machining of AISI L6 tool steel which is difficult to cut material. The output parameters under consideration are surface roughness, cutting energy, tool wear and Material Removal Rate (MRR). The optimization for multi-responses was carried out through Taguchi based Grey Relational Analysis (GRA). For experimental design, tests were based on L9 orthogonal array. According to the GRA optimization results, optimum cutting speed level was 160 m/min and the feed rate was 0.16 mm/ rev. The percentage improvement in Grey Relational Grade (GRG) was calculated as 19.07%, thus showing the advantage of using the GRA.

Keywords. Sustainable manufacturing, cryogenic machining, hardened steel, energy consumption, tool life.

1. Introduction

L6 is one of the low alloy special purpose tool steels containing 1.5wt% nickel which results in an increase of its toughness. The increased percentage of nickel, along with chromium and vanadium enhances the hardenability of this material. These characteristics make it difficult to machine. Machining of hardened material is normally slow and reduces overall tool life resulting in an increase in machining cost. Moreover, hard machining requires ultra-hard and extremely rigid machine tools which further increase the overall product costs [1]. The conventional cutting fluids have been applied to enhance the efficiency of the cutting process with better service quality and enhanced tool life in comparison with dry machining. However, conventional cutting fluids are a

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source of environmental pollution and health hazards. The recycling of these cutting fluids is also difficult and expensive [2]. This shifts the focus on alternative strategies such as cryogenic-LN_2 for sustainable manufacturing that reduces the temperature significantly. After impinging on the cutting zone, LN_2 evaporates into the environment with no health hazards or disposal mechanism. Islam et al. [3] have compared cryogenic cooling with dry and conventional flood cooling under the machining of hardened EN-24 steel. Comparative results depicted improved surface quality, reduced cutting force, increased tool life and favourable tool wear pattern under cryogenic cooling. The better surface finish was associated with preservation of tool sharpness and ease in chip evacuation; lower cutting forces were attributed to friction reduction and cushion effect; increased tool life and favourable tool wear pattern were related to effective cooling and lubrication. Sivaiaha and Chakradhar [4] have compared the effect of cryogenic coolant with MQL, wet and dry machining in turning of 17-4 PH stainless steel. During the research, cryogenic machining provided better results in terms of tool wear (flank and rake), chip thickness and surface finish.

The Taguchi method presents a parameter design to form a process less variable. It also includes a tolerance design to specify the improvement in product quality. It permits multifactorial target-oriented optimization, in which the quality loss function is used to improve the properties of the product and the standard deviation is minimum. The focus of this research is on the turning process for AISI L6 tool steel at different cutting speeds and feed rates under cryogenic cooling. The results are analysed through Taguchi method and an optimum solution for the machining of L6 tool steel is proposed.

2. Experimental Setup

Tool Steel AISI-L6 is being taken as workpiece material in the turning experiments. The hardness of the said material is about 58 HRC and chemical composition is provided in ref [5]. The length of the workpiece for experiments was 100mm and diameter of 50mm. All the turning tests were performed by CK-4060 CNC-turning machine with a maximum spindle speed of 12000rpm and equipped with 8kW motor power. The uncoated carbide tool YG-8 and CNMG tool holder assembly were used as tool arrangement. The tool rake angle was -1° and clearance angle of 10°~12°. A new cutting insert having constant geometry was used for each experimental run. Photograph of the experimental set-up is shown in Figure 1.

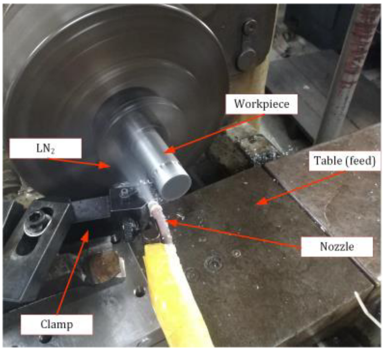

Figure 1. Cryogenic machining of AISI-L6 Tool Steel

In current work, turning experiments were performed under cryogenic cooling at three levels of cutting speed 100, 130 and160 m/min and three levels of feed rate 0.08, 0.12 and 0.16 mm/rev with a constant depth of cut of 1mm. In this study, Taguchi's L9 orthogonal array (OA) is used in Minitab software. The cutting parameters were selected according to the literature published and recommendations of cutting tool manufacturer. The cutting conditions can be found in literature such as [6], [7], [8].

3. Response Measurement

The present study focuses on surface roughness (μm), cutting energy (J), Material Removal Rate MRR (mm^3/min) and flank wear (nm). To represent surface roughness average surface roughness Ra was taken as major quality indicator of the machining process. Surface roughness values were measured at different locations through Mehr Perthometer SJ-410 on the workpiece and then a mean value was calculated to increase measurement accuracy. Cutting energy is related to the machining efficiency of the product. Cutting energy was measured through PPC current clamps. In order to achieve optimum machining results, MRR needs to be addressed. It is the product of cutting speed, feed rate and depth of cut. Tool wear directly affects production time and overall machining cost of the product. In this study, maximum flank wear (VBmax) is only considered as the parameter of wear. The measurements were carried out on workpiece material until the experimental process was completed and finally an average value of flank wear was calculated.

4. Result and discussion

This section provides the measurement results for surface roughness, cutting energy, MRR, and tool wear. The summary of the experimental results is presented in Table 1.

Table 1. Summary of experimental results

Exp. No.	Cutting speed (m/min.)	Feed Rate (mm/ rev.)	Surface roughness (Ra)	Cutting energy (J)	MRR (mm^3)	Flank wear (nm)	GRC SR	GRC CE	GRC MRR	GRC TW	GRG
1	100	0.08	1.33	296842	8000	78	0.5701	1	0.3333	0.3333	0.5592
2	100	0.12	1.45	341265	12000	109	0.4656	0.759	0.3928	0.4262	0.5109
3	100	0.16	1.71	406852	16000	126	0.3333	0.5598	0.4783	0.5778	0.4873
4	130	0.08	1.22	376852	10400	102	0.7176	0.6361	0.3667	0.4	0.5301
5	130	0.12	1.35	437387	15600	131	0.5495	0.4988	0.4681	0.4952	0.5029
6	130	0.16	1.54	495261	20800	156	0.4094	0.4135	0.647	0.6842	0.5385
7	160	0.08	1.1	469582	12800	116	1	0.4474	0.4074	0.52	0.5937
8	160	0.12	1.22	521268	19200	148	0.7176	0.384	0.579	0.6265	0.5768
9	160	0.16	1.41	576592	25600	182	0.496	0.3333	1	1	0.7073

*SR = Surface Roughness, CE = Cutting Energy, TW = Tool Wear

Surface Roughness (Ra)

Figure 2(a) has shown a decrease in Ra at higher cutting speeds and low feed rate. High surface roughness can be associated with large Build Up Edge (BUE) and Build Up Layer (BUL) areas on the tool's cutting edge at low cutting speeds. Similar results have been reported by Sarikaya and Güllü [6] in CNC turning for AISI 1050 steel. On the other hand, feed rate is directly proportional to the surface roughness. This is due to increase in feed force and volume of material removed in accordance with increase in feed rates. Jamil et al. [9] have also reported similar trends in the turning process.

Cutting Energy

Cutting energy is directly proportional to the cutting speed and feed rate provided in Figure 2(b). The relationships of cutting speed and feed rate with cutting energy are almost linear. At higher cutting speeds and feed rates, axis motor needs to move faster. This results in increasing the cutting energy [10].

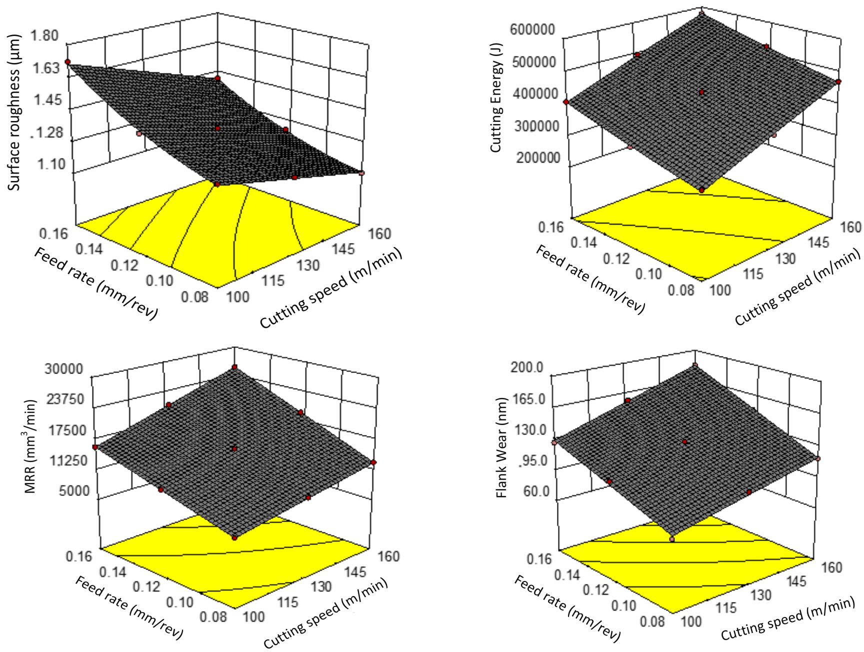

Figure 2. 3D surface plots for (a) surface roughness (b) cutting energy (c) MRR and (d) tool wear

Material Removal Rate (MRR)

MRR is derived from cutting speed and feed rate as per equation (1):

$$\mathrm{MRR} = v_c \times f \times a_p \quad (1)$$

Here v_c is cutting speed, f is feed rate and a_p is depth of cut. MRR is calculated from equation (1) for all experiments. Figure 2(c) depicts that MRR is directly proportional to cutting speed and feed rate and the relationship in both cases is linear.

Flank Wear

Figure 2(d) has inferred that flank wear is directly proportional to the cutting speed and feed rate. The straight-line slope in both cases indicates that the relationship of tool wear with cutting speed and feed rate is linear. This can be attributed to thermal softening of tool material at higher cutting speeds and feed rates [7]. However, the effect of feed rate is more pronounced than the effect of cutting speed on tool wear.

Multi-response optimization using grey relational analysis (GRA)

Taguchi based Grey Relational Analysis (GRA) was used for simultaneous optimization of surface roughness, cutting energy, MRR and tool wear. It involves correlation analysis of sequences with uncertainty and discrete data. It determines the degree of approximation through Grey Relational Grade (GRG). GRG was determined in the first step after the normalization of the experimental results. Three criteria are used in GRA which are “larger-the-better”, “smaller-the-better” and “nominal-the-best”. In the current research, our aim is to maximize the MRR, minimize the value of cutting energy, surface roughness and tool wear. The equations are discussed in detail in [2]. Table 1 provides a summary of GRC and GRG measurements. From Table 1, we can see that the ninth experiment gives the highest value of GRG which means that it has the best multi-performance characteristics. Analysis of Variance (ANOVA) is a statistical method which is used to examine the interactions of all the control factors under consideration [1]. The results show that model is significant, cutting speed (A), feed rate (B), products AB, A^2 and B^2 are all significant factors having a significant impact on GRG values. The value of $R^2 = 0.9969$ and adj. $R^2 = 0.9918$ are very close to each other which shows the reliability of data.

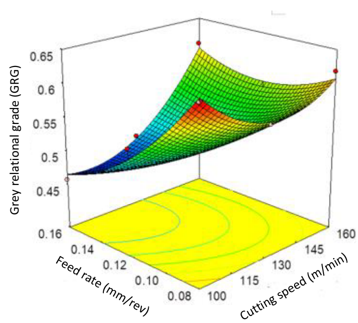

Figure 3. 3D Plot for grey relational grade

The 3D plot for GRG presented in Figure 3 shows that GRG values initially decrease with an increase in cutting speed up to 130 m/min and afterwards the relationship becomes direct and linear at higher cutting speeds. On the other hand, GRG is directly proportional to feed rate. The confirmation experiments of the control factors have been performed at optimal and random levels to verify the accuracy of optimized results and determine the improvement in overall output value. Table 2 compares the estimated GRG with the experimental value. The improvement in GRG from initial factor combination (V3-F2) to optimal factor combination (V3-F3) was 0.1139, showing a percentage improvement of 19.07%. Similarly, Sarikaya and Güllü [2] and Kumar and Sahoo [8] have shown the improvement in GRG from initial parameter combination to the optimal parameter combination amounting to 39.4% and 54.5 % respectively.

Table 2. Results of the confirmation experiment

Initial cutting conditions		Optimal cutting conditions	
		Predicted results	Experimental results
Level	V3-F2		V3-F3
Surface Roughness	1.54		1.4
Cutting Energy	495261		576590
MRR	20800		25698
Tool Wear	102		77
GRG	0.5973	0.7106	0.7112
Improvement in GRG = 0.1139;		The % improvement in GRG = 19.07%	

5. Conclusions

In this paper, the cutting parameters were optimized through Taguchi based GRA with the multiple-performance outputs. The ANOVA results indicate that cutting speed and feed rate both are significant factors affecting the cutting performance. According to the ANOVA results for GRG, the percentage contributions of feed rate and cutting speed are 46.57 % and 15.91 % respectively. Therefore, feed rate is the most significant control factor on GRG for minimization of surface roughness, cutting energy and tool wear and maximizing MRR. Taguchi based GRA directly combines the multiple responses into a single performance characteristic known as Grey Relational Grade (GRG). The GRG results depicted that the best combination values were cutting speed of 160 m/min. and feed rate of 0.16 mm/ rev. The improvement in GRG from initial factor combination (V3-F2) to optimal factor combination (V3-F3) was 0.1139, showing a percentage improvement of 19.07%.

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